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ACOUSTIC ATTENUATION IN THE DEEP OCEAN BELOW 2000 HZ, (U)
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(6) ACOUSTIC ATTENUATION IN THE DEEP OCEAN

BELOW 2000 Hz

By

(10) J. T. /GOTTWALD
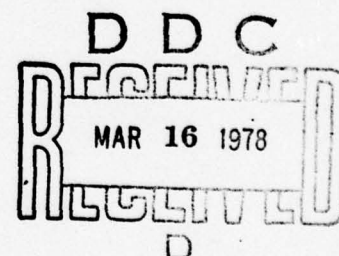
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ACOUSTIC ATTENUATION IN THE DEEP OCEAN

BELOW 2000 Hz

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J. T. GOTTWALD

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1. INTRODUCTION

All acoustic energy propagated in the deep ocean is ultimately degraded into some form of heat energy. The sources of the dissipation are generally divided into two catagories: those due to dissipation of acoustic energy in the transmitting medium and those associated with conditions at the boundaries of the medium. In the deep ocean where long paths exist apart from boundary reflection, the dissipation of acoustic energy into the medium itself is of extreme importance.

Attenuation is the term used to describe the decrease in acoustic energy by means other than spreading. Attenuation is caused by absorption in the medium along the propagation path, by scattering from the propagation path, and by leakage from the path through the interaction of the path size and the acoustic wavelength. The absorbed energy is converted to heat and is lost as acoustic energy. The scattered energy and the energy lost through leakage may be rescattered, absorbed at a boundary or absorbed in the medium. Each of these mechanisms is predominate over a unique part of the acoustic spectrum.

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2. SUMMARY

This report presents a brief summary of existing acoustic attenuation mechanisms and attenuation data. An emperical relation between the attenuation and frequency is developed which fits the available data below 2000 Hz to within 16%. This expression is given by

$$\alpha = 0.0265f^{3/4}$$

where f is in KHz and α is in dB/Kyd. This expression was developed from the data of Thorp, Kibblewhite, et-al., and Urick. No attempt was made to correlate the attenuation coefficient at low frequencies with temperature, depth or salinity since the quantity of available data is not sufficient and the scatter of the data is too large.

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3. SUMMARY OF ATTENUATION MECHANISMS

The three principal attenuation mechanisms which result in conversion of acoustic energy into heat energy and a resulting decrease in available acoustic energy are as follows:

(a) Viscous losses, resulting from relative motion occurring between various portions of the medium during the compressions and expansions that accompany transmission of an acoustic wave.

(b) Heat conduction losses which occur when heat flows from the high pressure to the low pressure areas accompanying the propagation of an acoustic wave.

(c) Molecular exchange losses associated with changes in the molecular structure of the medium which are associated with the finite time that is required for the changes to take place. Each of these absorption mechanisms has been treated in detail by several authors (*References 1, 2, 3).

An expression for the absorption of acoustic energy by fluids due to viscous effects was originally derived theoretically by Lord Rayleigh. This expression was derived upon the assumption that the bulk or volume coefficient of viscosity associated with uniform compression of a fluid should be zero. This resulted in an expression for the absorption α of the form

$$\alpha = \frac{2\omega^2 \eta}{3\rho c^3} \tag{1}$$

where η is the shear coefficient of viscosity, ρ_o is the density of the fluid; C is the velocity of sound in the fluid and ω is the circular frequency of the acoustic wave.

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*Numbers in parenthesis in the text of this memorandum indicate references contained in the bibliography at the end of the memorandum.

It was later discovered that the assumption of a vanishing volume coefficient of viscosity was in error, producing absorption coefficients approximately 3 to 6 times smaller than measured for pure water. Inclusion of a non-vanishing volume coefficient of viscosity results in an expression for α in water of the form

$$\alpha = \frac{\omega^2}{2\rho_o C^3}\left[\frac{4}{3}\eta + \eta'\right] \tag{2}$$

where η' is the volume coefficient of viscosity. Direct measurement of the volume coefficient of viscosity indicates that η' in water is approximately three times the coefficient of shear viscosity. Substitution of measured values for ρ_o, C, η and η' into Equation 2 results in satisfactory agreement between theoretical values and measured values for pure water but does not explain the observed absorption for sea water.

Another mechanism which provides for conversion of acoustic energy into heat energy in the fluid is heat conduction. During the compression of the fluid, resulting from the passage of a sound wave, the temperature is raised and a temperature gradient is established locally. This leads to a flow of heat by conduction from the high pressure (higher temperature) region to the low pressure (lower temperature) region. For most fluids, the magnitude of this effect is small enough for all practical frequencies that a fairly simple theoretical equation results and the expression can be added to the viscous losses which occur. The resulting expression is given in Equation 3

$$\alpha = \frac{\omega^2}{2\rho_o C^3}\left[\frac{4}{3}\eta + \eta' + \frac{\kappa(\gamma-1)}{C_p}\right] \tag{3}$$

where κ is the thermal conductivity of the fluid, C_p is the specific heat at constant pressure and γ is the ratio of the specific heat at constant pressure to the specific heat at constant volume. As indicated, the conversion of acoustic energy into heat at normal frequencies is very small compared to the conversion by means of viscous effects. The ratio of the conversion by viscous effects to the conversion by heat conduction at $4^{\circ}C$ is 3×10^3. For all practical purposes, the effects of heat conduction can be neglected in water.

Figure 1 contains a graph of Equation 2 for a temperature of $5^{\circ}C$ for fresh water. Also included in Figure 1 is a plot of the measured attenuation in fresh water at $5^{\circ}C$, and a plot of the measured attenuation in sea water at $5^{\circ}C$. The agreement between Equation 2 and fresh water is within the range of the experimental error of the measurements and it is apparent from the curve for sea water at $5^{\circ}C$ that below 400 KHz there are additional processes producing absorption in sea water beyond those present in fresh water.

It is natural to attribute this additional absorption to the presence of dissolved salts in sea water and to refer to it as a type of chemical relaxation. Laboratory measurements by Leonard (4) and co-workers have shown that the excess acoustic absorption of sea water as compared to fresh water is caused almost entirely by the presence of dissolved $MgSO_4$. Liebermann showed theoretically (5), that the ionic relaxation mechanism together with viscosity should yield a frequency dependent absorption coefficient of the form

$$\alpha = A \frac{Sf_t f^2}{f_t^2 + f^2} + B f^2 / f_t^2 \qquad (4)$$

Schulkin and Marsh (6) developed a fit between this equation and some 30 thousand measurements made at sea between 2 and 25 KHz

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10^{-1}

10^{-2}
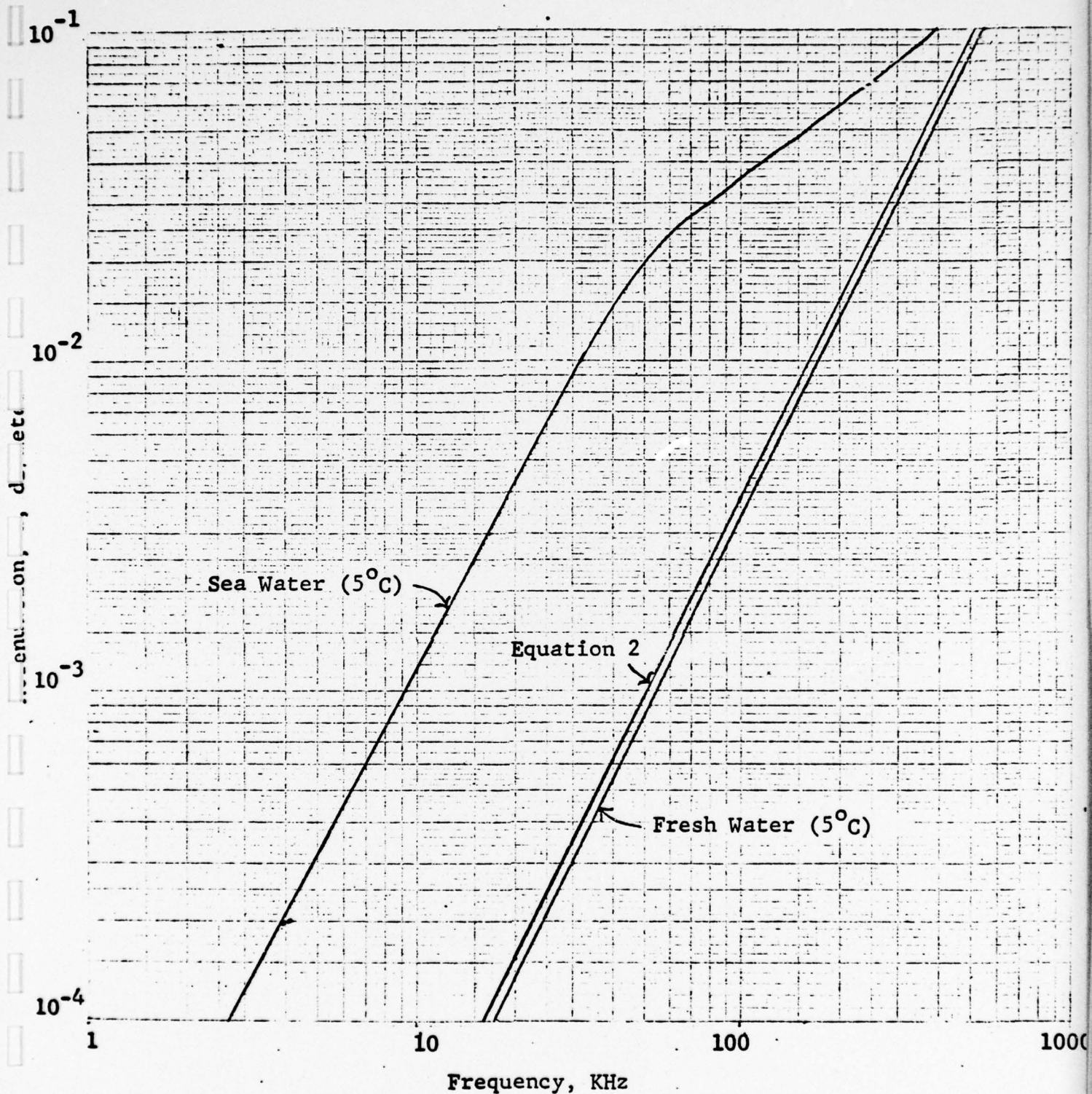
Attenuation, db/ft

10^{-3}

Sea Water (5°C)

Equation 2

10^{-4}

Fresh Water (5°C)

1   10   100   1000

Frequency, KHz

Figure 1 - Attenuation in Fresh and Salt Water at 5°C compared with absorption alone at 5°C.

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out to ranges of 25 Kyds. The following values for the terms in Equation 4 were developed:

$A = 1.36 \times 10^{-2}$

$B = 2.68 \times 10^{-2}$

S = Salinity in parts per 1000 of sea water, $^{o}/oo$

f = Frequency in KHz

f_t = Temperature dependent relaxation given by

$$f_t = 21.9 \times 10^{6-\left(\frac{1520}{T+273}\right)} \qquad (4a)$$

At high frequencies ($f >> f_t$) the second term in Equation 4 becomes dominant. This is the term associated with viscous absorption and is proportional to the square of the frequency. When f has a value in the neighborhood of f_t, the absorption varies in a very complicated fashion; both with frequency and temperature. Figure 2 presents the same measured curve for sea water at $5^{o}C$ that is presented in Figure 1 and, in addition, presents the attenuation in dB per meter at $5^{o}C$ as computed from Equation 4. It must be pointed out that Equation 4 is useful only for frequencies above 2 KHz and no attempt should be made to apply this equation in determining attenuation of sound in sea water at frequencies below 2 KHz.

The attenuation of acoustic energy from frequencies of 5 KHz up appears to be well understood in terms of viscous attenuation, heat loss, and chemical relaxation due to $MgSO_4$. However, for frequencies below approximately 5 KHz, measured attenuations depart from the theoretically derived expressions based upon the afore mentioned physical mechanisms, indicating that additional processes are involved in acoustic attenuation below frequencies of around 5 KHz. This is graphically illustrated in the compilation by Thorp (7) which is reproduced as Figure 3. It is apparent in Figure 3 that below 5 KHz, the measured attenuation data departs from the relaxation absorption curve of Schulkin
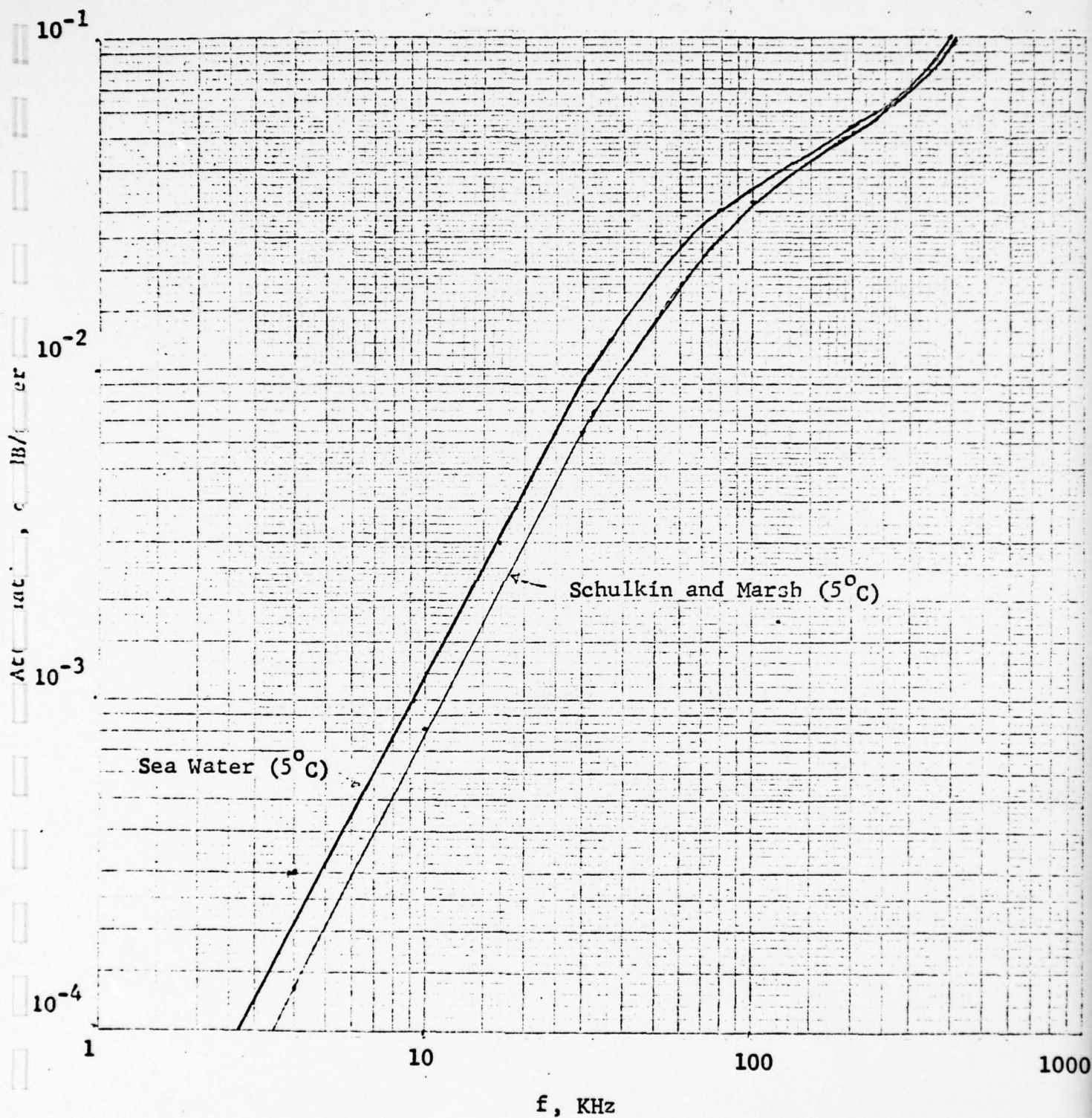
Figure 2 - Attenuation in Sea Water at 5°C compared with the equation of Schulkin and Marsh at 5°C. -8-
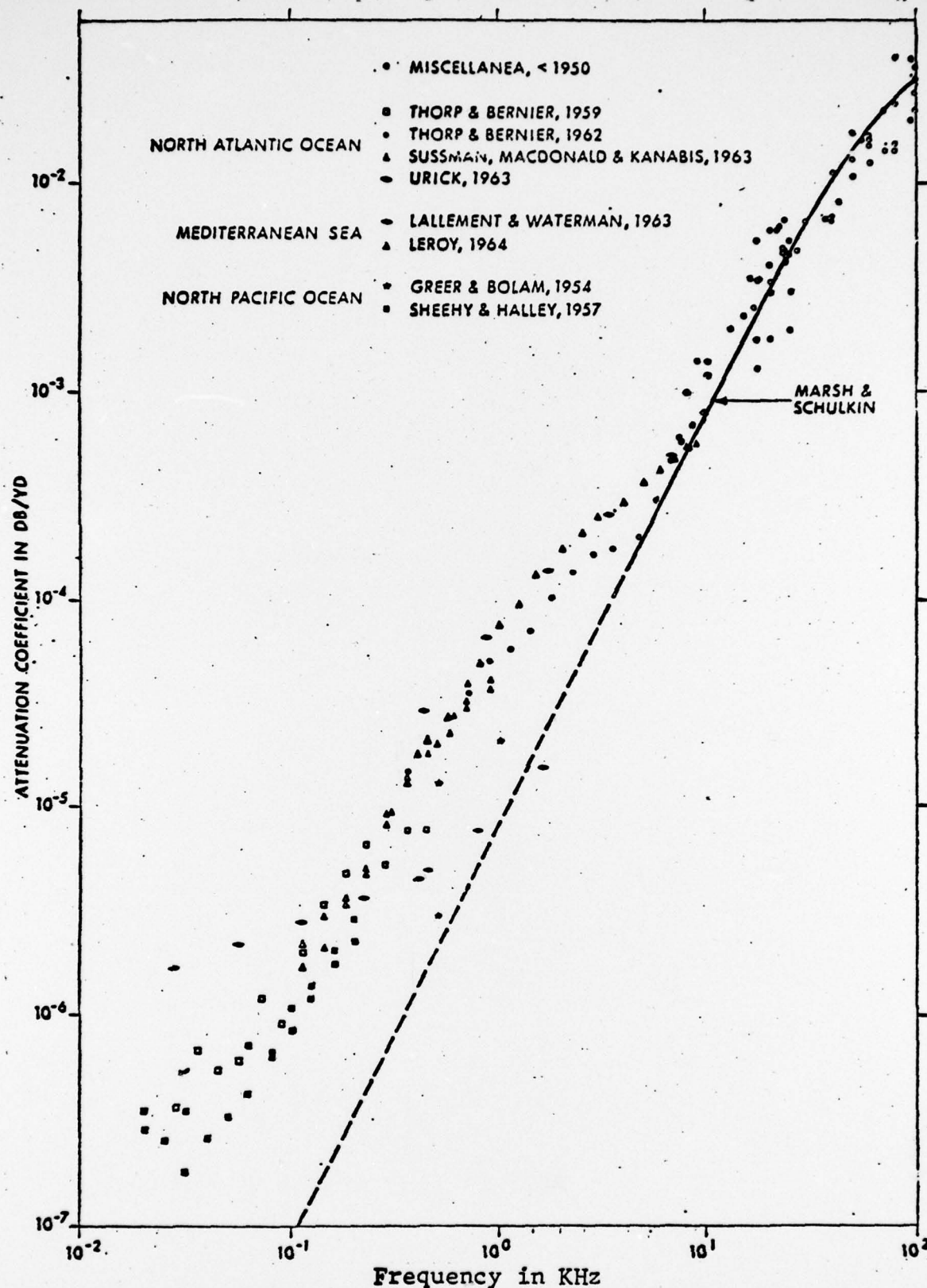
Figure 3 - Summary of attenuation measurements below 100 KHz. Origin and geographical area in which data were obtained since 1954 are indicated. The relaxation absorption curve for a depth of 4000 ft, temperature of 40°F, and salinity of 35% from Marsh and Schulkin is shown for comparison.

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and Marsh by approximately one decade. It is also apparent that at least one set of measurements, i.e., Urick (1963), varies from the general trend of the measured data particularly below 100 Hz. Subsequent measurements of very low frequency attenuation co-efficients by Kibblewhite et-al., and Urick indicate that below about 500 Hz additional physical mechanisms are involved in the attenuation process.

Measurements of attenuation at very low frequencies require the use of extremely long propagation paths. These paths exist only in the deep ocean and involve 3 modes of propagation:

      (a) RSR Modes

      (b) SOFAR Modes

      (c) Bottom Reflected Modes.

In general, Bottom Reflected Modes will be unimportant at very long ranges. The attenuation suffered via the RSR and SOFAR Modes in contrast will be very small and, in fact, at long ranges, the energy received will be mainly due to a finite number of trapped RSR and SOFAR Modes. If a shallow source is considered, then the relative degree of excitation of SOFAR Modes would be expected to be small and RSR Modes would predominate. As the frequency decreases, the number of trapped RSR Modes would tend to decrease and more energy would be lost by defraction and scattering into the bottom. However, temperature and salinity inhomogeneities can cause attenuation through a net transfer of energy from trapped to untrapped modes; this mechanism would be expected to become more efficient as the frequency increased. As a result, at very low frequencies, it would be expected that the attenuation would demonstrate a minimum at some particular frequency with the at-tenuation increasing both for decreasing and increasing frequency. This, in fact, has been observed by Kibblewhite et-at., and Urick in their recent measurements (8, 9, 10, 11, 12). Urick (8) discusses the scattering and leakage problem theoretically as applied to the SOFAR channel. Kibblewhite, Denham and Barker (10) discuss the leakage problem and the scattering problem as applied

to the RSR propagation paths. The resulting analyses are essentially identical except in the various details concerning the size of the tracks which are traversed by the rays and the actual path length involved for a given range, but the physical mechanisms involved are identical for both the SOFAR and the RSR propagation modes. Thus it appears that a theoretical explanation for the observed attenuation coefficients at very low frequencies is available.

The effect of pressure or depth on absorption has been investigated theoretically and experimentally using the resonator decay method. In the range of hydrostatic pressure found in the sea, the effect of pressure is to reduce the absorption coefficient as shown in Equation 5

$$\alpha_d = \alpha_o(1-1.93 \times 10^{-5} d) \qquad (5)$$

where α_d is the absorption coefficient at a depth d, α_o is the absorption coefficient at zero depth, and d is the depth in feet. When Equation 5 is combined with Equation 4 and the attenuation is computed as a function of depth for a typical velocity profile in the deep ocean, the curve of Figure 4 results. This curve is computed for a frequency of 4 KHz and salinity 35 parts per thousand. This figure illustrates the combined effects of temperature and pressure variations upon the attenuation coefficient. In the upper 3 to 4 thousand feet, the predominant factor is the decreasing temperature which causes an increase by a factor of 2 in the attenuation coefficient. Below 3000 feet the temperature becomes constant and the principal factor is the increase in depth or pressure which causes a decrease in the attenuation coefficient of about 15% of the value at 4000 feet. Figure 4 particularly illustrates the errors which can be encountered if near surface attenuation values are used in figure of merit computations for RSR or Reliable Acoustic Paths systems. Since,
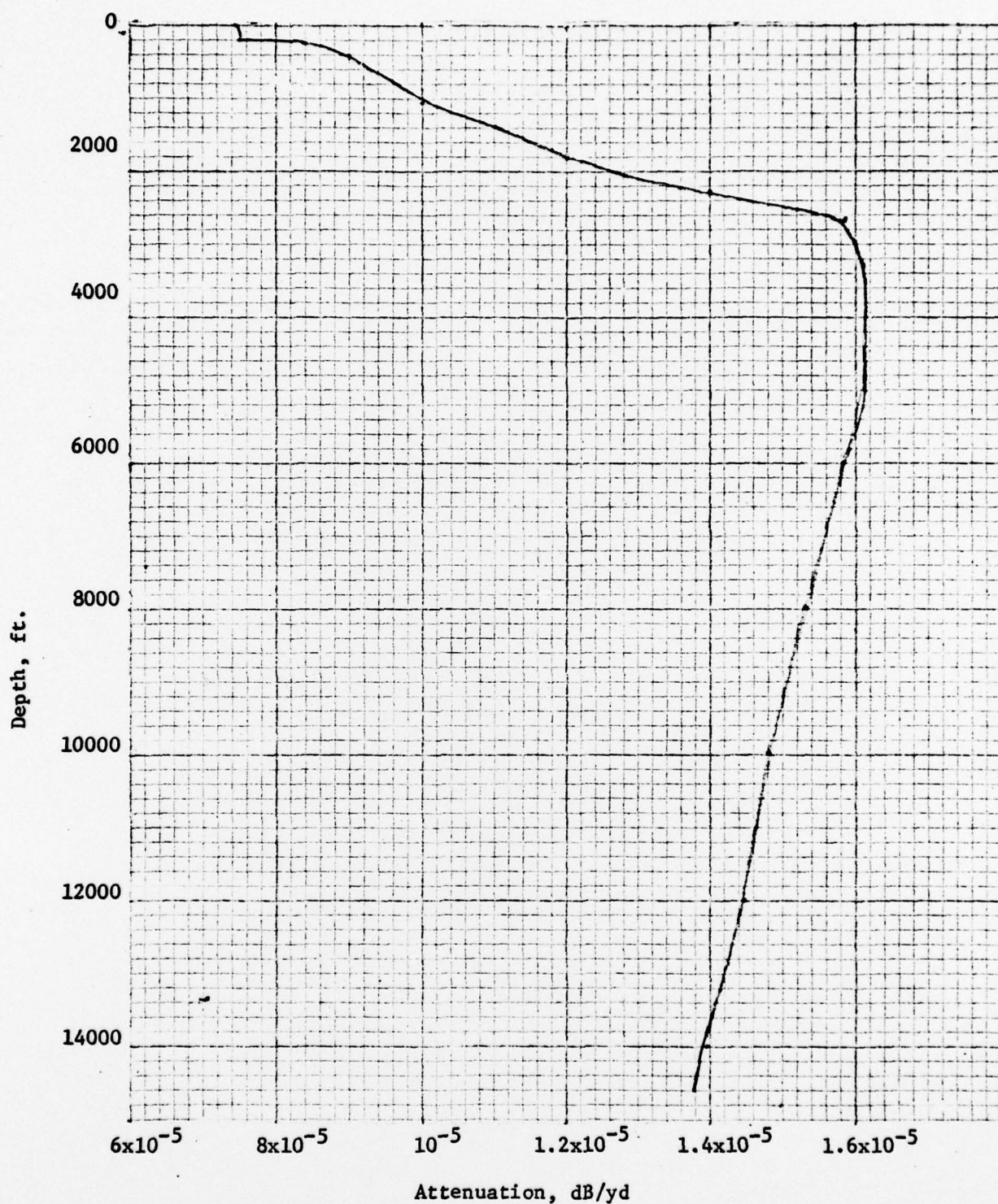
Figure 4 - Attenuation as a function of depth for a typical deep ocean thermal profile (computed from Equation 5) f_o = 4 KHz

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in those cases, approximately 80% of the traveled path lies below 2000 feet, the use of near surface attenuation coefficients would result in an error of a factor of 2 in the correct attenuation value.

In reference to Equation 5, and Figure 4, it should be pointed out that these results are known to be applicable for attenuation at frequencies above 2 KHz. Below this frequency other mechanisms predominate in the attenuation and, as yet, the effect of pressure at extremely low frequencies has not been fully investigated or documented.

In summary, there are three principal mechanisms which produce attenuation of acoustic energy in the ocean. These are:

(1) Absorption of energy by means of viscous and molecular exchange phenomena.

(2) Scattering of acoustic energy by means of thermal and chemical inhomogeneities in the water.

(3) Leakage of acoustic energy from propagation modes. Absorption appears to be the predominant cause of attenuation above 2 KHz. In the region from 10 Hz to 2 KHz the predominant mechanism appears to be scattering and below 10 Hz leakage appears to be the predominant mechanism.

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4. SUMMARY OF MEASURED ATTENUATION COEFFICIENTS
FOR THE DEEP OCEAN

Thorp (7) has provided a summary of some of the measured
values for deep ocean sound attenuation prior to 1965. Since
that time, Urick and Kibblewhite, et-al., have provided a large
number of measured values of deep ocean sound attenuation. As
was noted in the previous section, below 5 KHz the measured values
deviate significantly from the values as computed from Schulkin
and Marsh. Subsequent measurements have shown that the deviation
is even greater in the frequency region below 1 KHz. Figure 5
is a summary of the measured values reported by Urick and Kibble-
white et-al. The value of the attenuation as computed from
Equation 4 and plotted in Figure 3, is also plotted in Figure 5
for reference purposes. It will be noted that for frequencies
below 100 Hz, the error arising from using Equation 4 will amount
to a factor of 10 to 20. The large spread of the data between 10
Hz and 1 KHz is indicative of at least 2 factors:

(1) The size of the attenuation coefficient in this
frequency band requires the use of extremely long propagation
paths for measurements. The propagation loss introduced by
spreading, must be subtracted from the net propagation loss to
obtain the propagation loss or attenuation over the path, thus
the propagation over the path must be well understood. It is
not too difficult to correct for propagation in the SOFAR or deep
sound channel provided that the velocity profile information is
available, but bottom contour information must be available and
the effect of near surface channeling must be accounted for so
that an adequate description of spreading loss can be included in
the experiment.

(2) The value of the attenuation coefficient at low
frequencies necessitates extreme care in the calibration of the
equipment used in the measurements. Any slight inaccuracies,
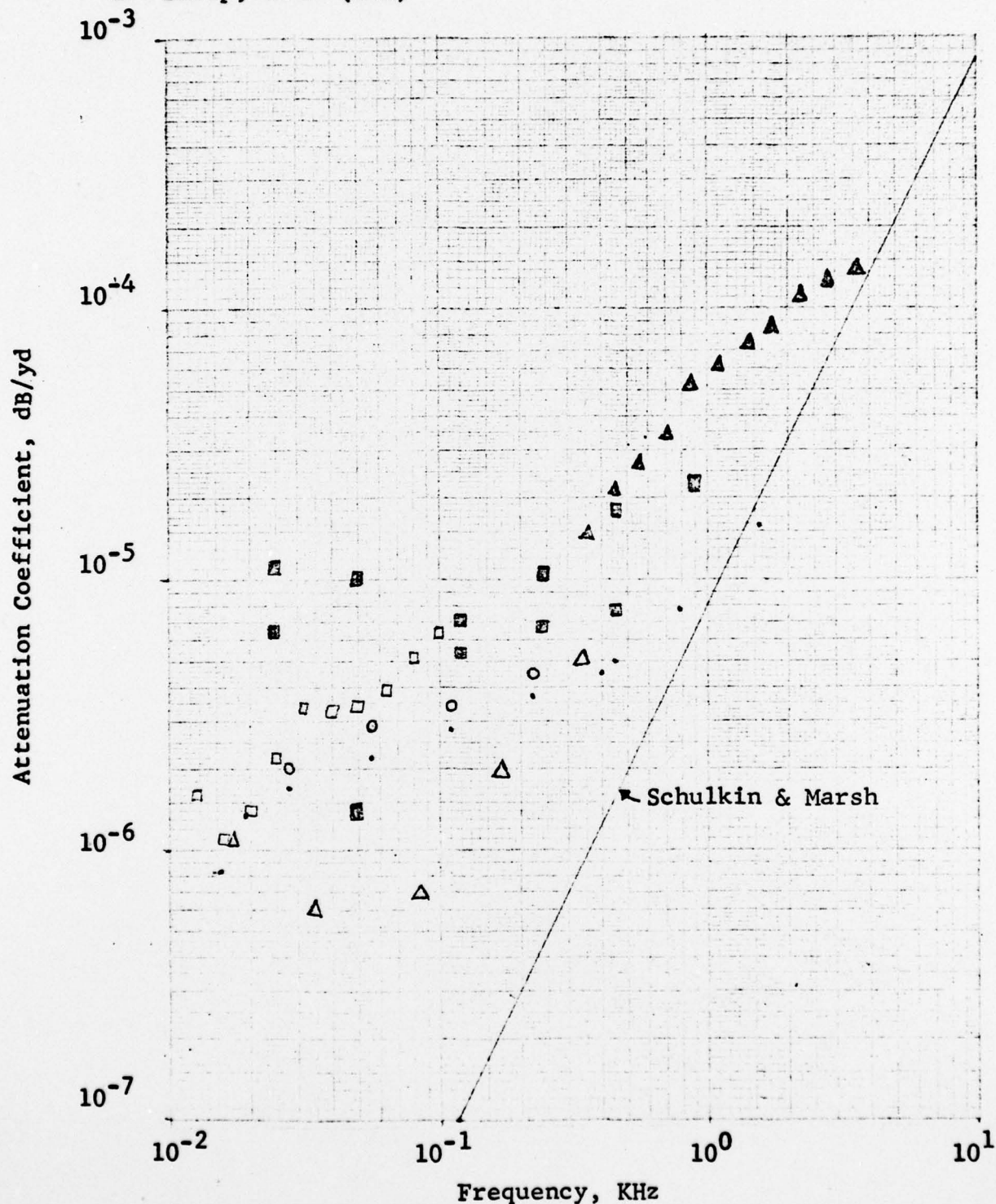errors or systematic shifts in the calibration of the equipment

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Figure 5 - Measured Attenuation Versus Frequency

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will produce fairly large inaccuracies in the measured attenuation
coefficient, and the spread observed in Figure 5 is probably due
in some measure to slight inaccuracies in the calibration of the
equipment used. This is further confirmed by the apparent
randomness of the measured values in any given octave.

A third factor which was initially believed to cause an error
was the use of explosive sources in the experiments. The measure-
ments of Thorp were made using a coherent source and the general
agreement between those measurements and the other measurements
plotted in Figure 5 indicates use of explosives does not induce
any undesirable or unknown effects into the measurements.

It will be noted that the results of the work by Sheehy and
Halley (13) is not included in Figure 5. The reason for this
is that the results of Sheehy and Halley were relative rather
than absolute measures of the attenuation and they are, therefore,
of little aid in determining the absolute value of the attenuation
coefficient. Those results do, however, have a form very similar
to those results plotted in Figure 5, and if the value of attenua-
tion obtained by Sheehy and Halley is normalized so that attenua-
tion coefficient is 1.8×10^{-6}dB/yd at 40 Hz, then the other values
cluster among those values plotted.

## 5. USEFUL EXPRESSIONS FOR ATTENUATION BELOW 2.0 KHz

As a result of each set of measurements indicated in Figure 5, each observer postulated an empirical relation between attenuation and frequency. These postulated relations are plotted in Figure 6 for comparison purposes. The length of each curve in Figure 6 defines the frequency range over which the various expressions are valid. While each of the seven expressions presented in Figure 6 represents, to some extent, the measured data as obtained by various observers, none of these expressions satisfies an average value for the entire data sample. The expression proposed by Thorp satisfies the measured data between the frequencies 300 Hz and 1500 Hz fairly well. The two expressions from Urick fit Urick's data fairly well and the one expression from Kibblewhite et-al., fits the upper value of their measured data fairly well. None of these expressions, however, are general enough or agree well enough with the body of data to be used over an appreciable range of frequencies, such as 10 Hz to 1 KHz or even perhaps 5 KHz. A least square fit of the data in Figure 5 to a power function

$$\alpha = af^d$$

was performed. The resulting attenuation expression is given by

$$\alpha = 1.49f^{3/4} \times 10^{-7} \, dB/yd \ (f \ in \ Hz). \qquad (6)$$

The correlation between Equation 6 and the data of Figure 5 is 84.5%. It is recommended that Equation 6 be used to compute underwater acoustic attenuation coefficients in the frequency range from 10 Hz to 2000 Hz until additional data becomes avail-

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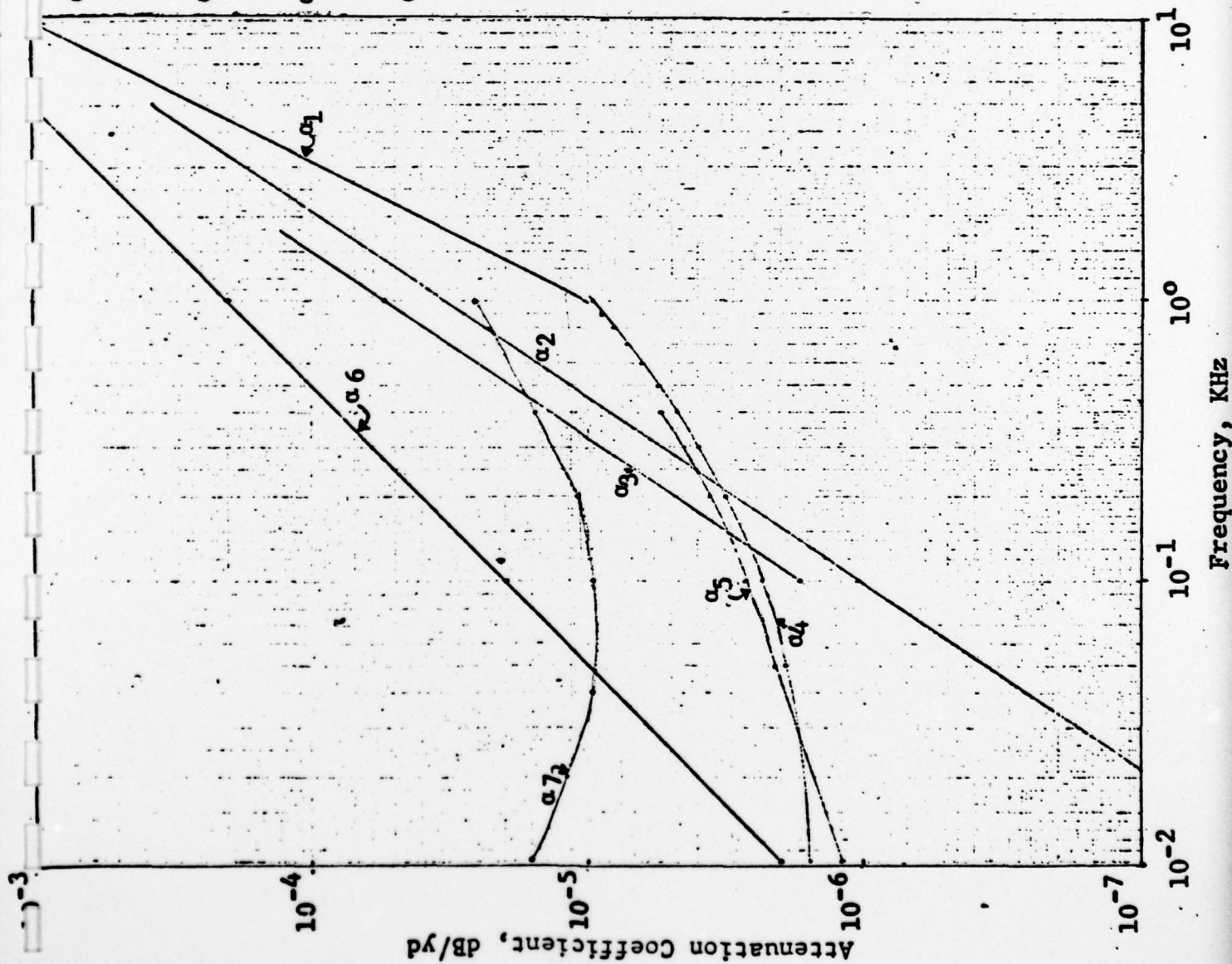
α_1 - Low Frequency Limit of Schulkin & Marsh (5°C),
$$\alpha_1 = 10^{-5}f^2 \text{ dB/yd, } f \text{ in KHz}$$

α_2 - Sheehy & Halley,
$$\alpha_2 = 3.3 \times 10^{-5}f^{3/2} \text{ dB/yd, } f \text{ in KHz}$$

α_3 - Thorp,
$$\alpha_3 = 5.42 \times 10^{-5}f^{3/2} \text{ dB/yd, } f \text{ in KHz}$$

α_4 - Urick (1964),
$$\alpha_4 = (1.5 + 8.1f) \times 10^{-6} \text{ dB/yd, } f \text{ in KHz}$$

α_5 - Urick (1963),
$$\alpha_5 = (5.6f^{1/3} + 8.5f^2) \times 10^{-6} \text{ dB/yd}$$

α_6 - Horton,
$$\alpha_6 = 2f \times 10^{-4} + 1.5f^2 \times 10^{-7} \text{ dB/yd,}$$

α_7 - Kibblewhite et-al.,
$$\alpha_7 = (\frac{89}{f} + 6.8 + 1.87f \times 10^{-2}) \times 10^{-6} \text{ dB/yd, } f \text{ in Hz}$$

Figure 6

Seven emperical expressions for acoustic attenuation at low frequencies.

Attenuation Coefficient, dB/yd

Frequency, KHz

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able whereby a better expression may be developed.

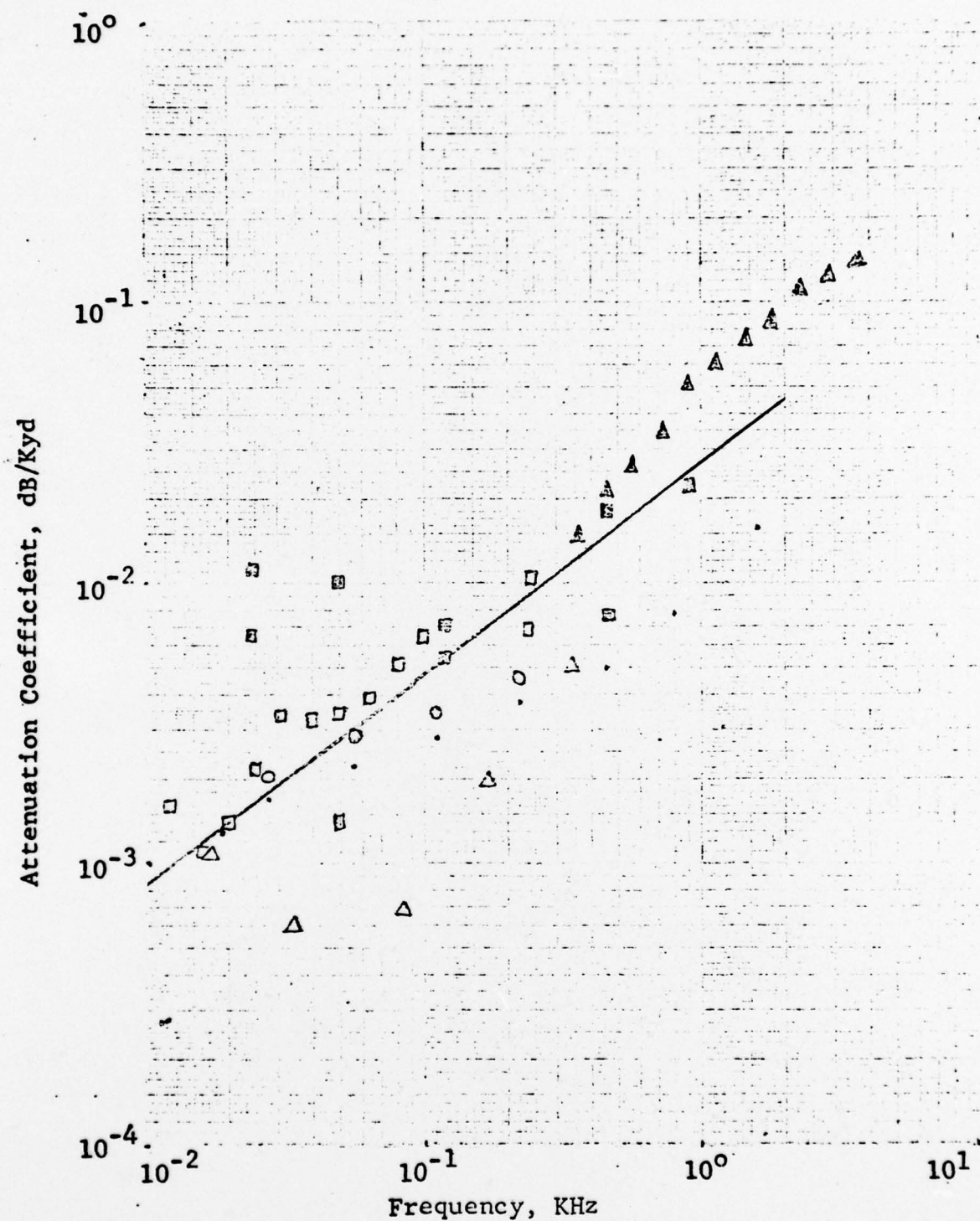Figure 7 is a plot of Equation 6 and the data from Figure 5.

Figure 7 - Attenuation Coefficient Versus Frequency
Showing The Expression   .0265f$^{3/4}$dB/Kyd

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